

The Impact of Map and Data Resolution on the Determination of the Agricultural Utilisation of Organic Soils in Germany

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Abstract Due to its nature, agricultural land use depends on local site characteristics such as production potential, costs and external effects. To assess the relevance of the modifying areal unit problem (MAUP), we investigated as to how a change in the data resolution regarding both soil and land use data influences the results obtained for different land use indicators. For the assessment we use the example of the greenhouse gas (GHG) emissions from agriculturally used organic soils (mainly fens and bogs). Although less than 5 % of the German agricultural area in use is located on organic soils, the drainage of these areas to enable their agricultural utilization causes roughly 37 % of the GHG emissions of the German agricultural sector. The abandonment of the cultivation and rewetting of organic soils would be an effective policy to reduce national GHG emissions. To assess the abatement costs, it is essential to know which commodities, and at what quantities, are actually produced on this land. Furthermore, in order to limit windfall profits, information on the differences of the profitability among farms are needed. However, high-resolution data regarding land use and soil characteristics are often not available, and their generation is costly or the access is strictly limited because of legal constraints. Therefore, in this paper, we analyse how indicators for land use on organic soils respond to changes in the spatial aggregation of the data. In Germany, organic soils are predominantly used for forage cropping. Marked differences between the various regions of Germany are apparent with respect to the dynamics and the intensity of land use. Data resolution mainly impairs the derived extent

of agriculturally used peatland and the observed intensity gradient, while its impact on the average value for the investigated set of land-use indicators is generally minor.

Keywords Peatland · Agriculture · Modifiable areal unit problem · Land use intensity

Introduction

Due to its nature, agricultural land use depends on the characteristics of local sites regarding production potential, costs and external effects. For instance, the vulnerability of land to water erosion depends on various factors that are influenced by site characteristics (e.g., slope, soil type and precipitation) and agricultural activities (e.g., plot layout and periods without vegetation cover). Thus, to quantify the relevance of agriculture's external effects, site-specific information is frequently required concerning both land use and various site characteristics. This information is needed particularly if decisive site characteristics correlate with relevant forms of land use.

Greenhouse gas (GHG) emissions that result from agricultural land use (i.e., excluding emissions related to fertilizer application, ruminant digestion and manure storage and application) are prominent examples of such a site-dependent external effect. Under a temperate climate, these emissions are negligible on mineral soils as soon as soil organic carbon has reached a new equilibrium after a land use change (Poeplau and others 2011). Within this transition phase, which lasts approximately 20 years, the conversion of grassland or forest to arable land induces an emission of $9 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ a}^{-1}$ (Poeplau and others 2011). However, on peatland, the impacts of agriculture on GHG emissions are different. Undrained peatland

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accumulates plant remains in waterlogged conditions over thousands of years. If these areas are drained, which is a precondition for their intensive agricultural use, the organic material oxidizes, and the peatland switches from being a net sink of GHG to being a net emitter. According to reviews by Höper (2007) and Oleszczuk and others (2008), in temperate climates, these emissions are on the order of 40 Mg CO₂ ha⁻¹ a⁻¹ for arable land and 17 Mg CO₂ ha⁻¹ a⁻¹ for intensively managed grassland. If aerobic conditions are maintained, these emissions only cease when the organic layer is more or less completely mineralized. This mineralization period can last for more than a century depending on the initial depth of the organic layer (Schothorst 1977).

In Germany, the emissions from agriculturally used peatland were equivalent to 4 % of the total German GHG emissions in 2008 or 37 % of the GHG emissions related to agriculture (UBA 2010). Obviously, German policies that attempt to successfully reduce GHG emissions must tackle this issue. In most cases, the GHG emissions from the cultivation of peatland can only be markedly reduced if the water table is raised, which requires an abandonment of agriculture or, at least, a significant reduction of land use intensity (Höper 2007). The abandonment of the cultivation of peatland would be an effective policy to reduce national GHG emissions, but questions remain as to whether this practice is a relatively efficient measure from the national perspective and whether it is effective on a global scale. For both questions, information is needed on both the type and amount of commodities that are actually produced on peatland in order to calculate the abatement costs on a national level and to assess the indirect land use effects induced by reallocation of production (cf. Searchinger and others 2008; Havlik and others 2011).

In a first step toward answering these questions, we analyzed the agricultural use of peatland in Germany. According to Haenel (2010), >75 % of the German peatland is used for agriculture, and in particular for forage cropping (i.e., dairy or suckler cow farming) (Röder and Grützmacher 2012). However, these farming systems display a wide range of intensities and levels of profitability. To assess the mitigation costs of rewetting peatland, data on land use beyond the information concerning whether a field is used as grassland or arable land should be regarded. These data, such as the composition of the regional herd or stocking density, cannot be derived from remote sensing. Unfortunately, for large areas, high-resolution (site-specific) data are not available, or its use poses certain problems. This lack of available data is true for both aspects, i.e., the information on land use beyond its utilization as grassland or arable land, and information on specific soil characteristics. First, the provision of statistical data on land use is limited by legal constraints concerning the

protection of personal information (Eurostat 2009). Second, if agricultural census data are used, the likelihood of an allocation error regarding land use increases with the spatial resolution, as a farm's land use is allocated according to the location of the farmstead and not the location of its fields. Third, the extent of peatland is not static because peatland may degenerate in the course of the mineralization of organic soils (Eggelsmann and Barthels 1975). This is particularly problematic since the original field data sources that were used for the delineation of peatland are often nearly 100 years old (Zitzmann 2003).

If data analyses are based on spatially aggregated data, problems may emerge which are summarized under the heading “Modifiable Area Unit Problem” (MAUP) (Openshaw and Taylor 1979). The MAUP describes the phenomenon that the results of an analysis depend on the scale on which the analysis is conducted (scale effect) and/or the way the data are aggregated (zoning effect). To assess the relevance of the MAUP in the context of the agricultural utilization of German peatland, we compared the analysis results with data based on different resolutions. For this purpose we used two different sets of soil data, the Soil Map of Germany (BGR 2010) and the Geological Map of Germany (BGR 2003) and intersected these data with information on agricultural land use that was aggregated at farm, municipality and county level. Aside from the data resolution's influence on the results, we were interested in the following two questions: How does land use respond to an increasing share of peatland, and how does the intensity gradient (particularly with respect to stocking density and land management) on peatland look?

Materials

Soil Data

We delineated the distribution and extent of peatland with the help of the Soil Map of Germany at a scale of 1:1,000,000 (BUEK) (BGR 2003) and the Geological Map of Germany at a scale of 1:200,000 (GUEK) (BGR 2003). A particular problem in the context of this study is that the relevant definitions used at the national and international level to delimit the soil type of interest do not coincide. Generally, three different terms must be separated: “Moor,” used in the German classification and mapping systems (Ad-hoc AG Boden 2005); “Histosol,” defined according to FAO (2006) and organic soil (IPCC 2006, Annex 3A.5). The last is the category relevant for the reporting of GHG emissions under the Kyoto-protocol. The definitions differ mainly in the following aspects: the required thickness of the organic horizon, the minimum content of soil organic matter, whether the organic horizon

must start at the soil surface and whether pedogenesis is considered. Generally speaking, the German definition is the most rigid of the three and the IPCC is the least.

In case of the BUEK, we derived the extent of peatland by selecting the soil type associations “Leitbodenassoziationen” no. 6 (fens) and no. 7 (raised bogs). We did not include other soil type associations that may include peatland because neither the “exact” location nor the extent of peatland in these associations is stated. This procedure is equivalent to the algorithm used for the German GHG inventory (Haenel 2010, p. 351).

In the case of the GUEK, we extracted the polygons with an organic top layer, classified as fen, (Niedermoor), raised bog (Hochmoor), bog (Moor), peat mixed with sand (“Sandmischkultur”) or a specific limnic soil (“Detritusmudde”). According to the German team that determines the GHG emissions from organic soils, these categories unquestionably qualify for the IPCC 2006 definition of organic soils (A. Gensior, pers. communication). Because the first three categories account for >96 % of the selected area, we also labeled this selection peatland. We refrain from the term organic soil because we did not include polygons that might also qualify as organic soils according to the IPCC definition and cover a far larger area (e.g., “Anmoor,” or peatland covered by an inorganic top-layer).

Land Use Data

We derived the location and distribution of grassland and arable land from the Digital Landscape Model (DLM) for Germany (BKG 2008). The DLM maps the distribution of different land uses at the scale of 1:2,500 and is based on remote sensing and topographic surveys. The DLM reflects the status as of September 2007.

The farm structural survey ((FSS): FDZ 2010) provides additional information on agricultural land use, such as stocks for all types of livestock (e.g., dairy cows, heifers and fattening pigs) and the area for all cultivated crops (e.g., maize, vegetables and vineyards), including grassland. These data are recorded for all German farms and are available for the years 1999, 2003 and 2007. Fields that do not belong to an active farm are not included. In most cases, these fields are abandoned. The highest spatial resolution of the FSS is the municipality. In an average municipality, roughly 40 farms manage ~1,700 ha of agricultural land.

Regarding the merging of the FSS and DLM data, one must bear in mind that in contrast to the DLM, the FSS does not map activities according to the location of the fields but, instead, of the farmstead. This difference in the mapping rules may especially induce some bias in Eastern Germany and Schleswig–Holstein, where farm size in ha is large compared to the municipalities’ agricultural area.

Division of the Dataset

We divided our sample into four study areas to account for regional variation in German agriculture. The study areas reflect regions that differ in their contribution to the area of agriculturally used peatland and in their farm structure (Table 1). We selected the study areas on the basis of the German *Laender* (federal states). Specifically, the two study areas NW and NE are characterized by high shares of utilized agricultural area (UAA) on peatland. While only 38 % of the German UAA is located in these areas, >83 % of the agriculturally used peatland can be found in these two regions. In SE the farms are much smaller compared to the other two study areas and the distribution of the peatland is more scattered. CE groups all the *Laender* in the

Table 1 Definition of the study areas for the regionalized analyses

Laender	Share of national UAA on peatland		Share of national UAA	General farm structure
	BUEK (%)	GUEK (%)		
NW Schleswig–Holstein, Lower Saxony, (Bremen, Hamburg)	48	48	22	Large family farms
NE Mecklenburg–Western Pomerania, Brandenburg, (Berlin)	35	37	16	Large commercial farms
SO Baden–Wuerttemberg, Bavaria	10	9	27	Small family farms
CE All others	7	6	35	

Source Calculations based on BUEK, GUEK and DLM

NW north-west, NE north-east, SO south, CE center

BUEK soil map of Germany, GUEK Geological map of Germany

UAA utilized agricultural area

middle of Germany, where for climatic reasons peatland is restricted to very few areas.

Methods

We disaggregated the information up to the municipality level. This maximum resolution was determined by the resolution of the FSS. To allow the comparison of the data across years, we grouped the municipalities that exchanged land during the restructuring of local governments into single mapping units. This step reduced the number of mapping units from more than 12,000 to 10,060. For simplicity, we refer to these single mapping units as municipalities. Each municipality belongs to either a county (rural county) or constitutes a county of its own (urban county). Urban counties are generally characterized by a low number of farms and small UAA. For the analyses at the county level, we merged the 85 urban counties with adjacent rural ones to avoid problems regarding data protection regulations (cf. Eurostat 2009). This left us with 317 units (counties) for the following analyses.

In the first analysis, we compared the extent and regional distribution of agricultural land on peatland for the GUEK and BUEK. In a second step, we determined how the land use responds to an increasing share of agricultural land on peatland. We defined the share of grassland (p_{GL}), arable land (p_{AL}) or utilized agricultural area UAA (p_{UAA}) on peatland as the following (Eq. 1):

$$p_{GL,u} = \frac{A_{GL,P,u}}{A_{GL,T,u}}, p_{AL,u} = \frac{A_{AL,P,u}}{A_{AL,T,u}}, p_{UAA,u} = \frac{A_{GL,P,u} + A_{AL,P,u}}{A_{GL,T,u} + A_{AL,T,u}}, \forall u \in \{c, m\}, \tag{1}$$

where $A_{GL,P}$ and $A_{AL,P}$ are the respective areas of grassland (GL) and arable land (AL) on peatland, and $A_{GL,T}$ and $A_{AL,T}$ indicate the respective total areas in a given administrative unit. These shares were calculated for Germany in total and for each of the m municipalities and c counties.

For the calculation of the area of agriculturally used peatland, we intersected the DLM with the BUEK and the GUEK, respectively. Compared to the FSS, the DLM’s extent of grassland and arable land are 24 and respectively 9 % higher. Therefore, we further analyzed p_{GL} , p_{AL} and p_{UAA} that are derived from the DLM by the respective areas $A_{GL,T}$ and $A_{AL,T}$ taken from the FSS.

We assume that the FSS compared to DLM is more reliable with respect to the “true” agricultural use, therefore, we will focus on the results based on the FSS in the remainder of this paper.

The following analyses are based on two methods. Localization indices show the response of land use to an increasing share of peatland. Cumulative density plots

depict the intensity gradient (stocking density) regarding the agricultural use of peatland in different parts of Germany.

We used POSTGRES[®]8.2.13 and POSTGIS[®]1.3.3. to manage the geographical data and SAS[®]9.2 for statistical analyses.

Localization Index

A localization index can be perceived as a specialization index (Schmidt and others 2006). A value of one indicates that the relative level of the investigated activity in the analyzed group is equal to the relative level for the entire sample. A value >1 indicates that the activity is more frequent in the respective class than in the sample on average, and a value between zero and one that it is less frequent. Localization indices map the response of different dependent variables to a single independent variable on a common scale. This mapping facilitates the comparison of the strength of the response, particularly if the values and units for dependent variables differ.

Prior to the calculation of the localization indices, we grouped the municipalities and counties into different classes according to their respective values of p_{GL} , p_{AL} and p_{UAA} . The class limits are {0 %, 2.5 %, 5 %, ..., 22.5 %, 25 %, 30 %, ..., 100 %}. For each class, we calculated the localization index I for different activities (Eq. 2) as the dependent variable and plotted it against the appropriate shares of land on peatland with the following:

$$I = \frac{L_{i,j}/L_{..j}}{L_{i..}/L_{...}}, \tag{2}$$

where $L_{i,j}$ is the activity level (i.e., area cropped or heads of livestock) of i in the peatland share class, j , $L_{..j}$ is the total respective reference area (GL, AL, or UAA) in the peatland share class, $L_{i..}$ is the total aggregated activity level, and $L_{...}$ is the total respective reference area (adapted from Schmidt and others 2006).

We calculated $L_{i,j}$ in four ways to assess the impact of a changing resolution regarding the distribution of peatland on the results. From Experiments One to Four, the resolution becomes more general. In the first experiment, we used all of the available information (Eq. 3):

$$L1_{i,j} = \sum_{m \in j} \sum_{f \in m} (p_{AL,m} * A_{AL,f} * \lambda_{AL} + p_{GL,m} * A_{GL,f} * \lambda_{GL}) * s_{i,f}; \tag{3}$$

$$s_{i,f} = \frac{L_{i,f}}{A_{AL,f} * \lambda_{AL} + A_{GL,f} * \lambda_{GL}},$$

where $A_{AL,f}$ and $A_{GL,f}$ are the arable land and grassland of farm f , located in municipality m , $L_{i,f}$ is the activity level at the farm and λ_{AL} and λ_{GL} are binary variables that indicate whether arable land, grassland or both are the appropriate reference for the respective activity.

In the second experiment, we assumed that only information on $p_{UAA,m}$ is available, while detailed information on $p_{GL,m}$ and $p_{AL,m}$ are missing. Consequently, Eq. 3 simplifies to Eq. 4 as the following:

$$L2_{i,j} = \sum_{m \in j} \sum_{f \in m} p_{UAA,m} * (A_{AL,f} * \lambda_{AL} + A_{GL,f} * \lambda_{GL}) * s_{i,f}. \tag{4}$$

In the third experiment (Eq. 5), we assumed that information is only available on the county in which a given farm is located, while differentiated information regarding the shares of grassland and arable land $p_{GL,c}$ and $p_{AL,c}$ are provided with the following:

$$L3_{i,j} = \sum_{c \in j} \sum_{f \in c} (p_{AL,c} * A_{AL,f} * \lambda_{AL} + p_{GL,c} * A_{GL,f} * \lambda_{GL}) * s_{i,f}. \tag{5}$$

In the fourth experiment (Eq. 6), we used only county-level information on the location of the farm, and, analogous to Eq. 4, only $p_{UAA,c}$ is known as

$$L4_{i,j} = \sum_{c \in j} \sum_{f \in c} p_{UAA,c} * (A_{AL,f} * \lambda_{AL} + A_{GL,f} * \lambda_{GL}) * s_{i,f}. \tag{6}$$

Cumulative Density Plots

We calculated the cumulative density distribution in six different ways. These variants differ in the way the activity data is aggregated (farm, municipality or county level) and whether the share of peatland is calculated based on differentiated values for grassland and arable land (p_{GL} and p_{AL}) or on an intermediate (p_{UAA}).

Results

First, we present general information on the use of peatland. Next, we focus on the analyses of the distribution of grassland, maize, and the stocking density of all and of grazing livestock because forage cropping is of outstanding

importance for the use of peatland. If not indicated otherwise, the results presented here refer to the year 2007 because the differences between the years are generally small.

Extent and Distribution of Agriculturally Used Peatland in Germany

The two data sources used to delineate the distribution of peatland (GUEK and BUEK) agree on the general distribution of peatland in Germany (Table 1). High values of p_{UAA} were found in the northwestern portion of Lower Saxony, central Schleswig–Holstein, Mecklenburg–Western Pomerania, Brandenburg and the southern part of Bavaria. While peatland covers large contiguous areas in the North and East of Germany, its distribution is patchier in the South and is mostly restricted to the area south of the Danube.

Peatland covers $1.81 * 10^6$ ha according to the BUEK, while the GUEK reports only $1.42 * 10^6$ ha (Table 2). This difference of $0.40 * 10^6$ ha can be nearly exclusively attributed to the differences reported for Lower Saxony, Mecklenburg–Western Pomerania and Bavaria. In these *Laender*, the peatland area according to the GUEK is generally 30 to 40 % smaller than the respective figure derived from the BUEK. If both sources are intersected with the DLM, the results are identical for the grassland area on peatland. For forests and shrubs, the difference is proportional to the difference in the peatland area. However, the two analyses differ with respect to the other three land use types. The analysis based on the BUEK yielded markedly higher shares of arable land and other land uses on peatland, while even the reported absolute extent of swamps and wetlands was lower. The difference in the reported area for arable land on peatland explains 75 % of the total difference between the two analyses. According to both analyses, 10.9 % of Germany’s grassland is located on peatland, while, for arable land, the estimates range from 2.1 (GUEK) to 4.4 % (BUEK) of Germany’s arable land.

Table 2 Extent of different land use types on peatland (relative shares in brackets) in 2007

	Extent of different land uses (in 1,000 ha)	
	BUEK	GUEK
Arable land	582 (32 %)	271 (19 %)
Grassland	704 (39 %)	704 (50 %)
Swamp, wetland, heath and fallow	89 (5 %)	128 (9 %)
Forest and shrubs	265 (15 %)	214 (14 %)
Others (e.g., settlements; peat, gravel or sand pits)	170 (9 %)	101 (7 %)
Total	1,808	1,416

Source Calculations based on BUEK, GUEK and DLM
BUEK soil map of Germany,
GUEK geological map of Germany

The coarser scale of the BUEK implies that smaller peatland areas are ignored, while the extent of peatland is overestimated in areas where peatland is widespread. In contrast to the BUEK, the GUEK indicates that peatland is much more common in areas with an undulated terrain where peatland is restricted to river valleys and depressions as in southern Bavaria, Baden-Wurttemberg or eastern Schleswig–Holstein. In addition, according to the GUEK, regions with high shares of peatland are much more restricted. These differences in location between the two sources are highlighted by the fact that only $0.77 \cdot 10^6$ ha are mapped as peatland by both sources.

According to the BUEK, in roughly one-fifth (2,274 of 10,060) of the municipalities, at least some UAA is located on peatland. The number of municipalities with grassland on peatland slightly exceeds the number of municipalities with arable land, while the median value of the non-zero observations for $p_{GL,m}$ (28.5 %) is more than twice as high as that for $p_{AL,m}$ (13.1 %). However, the correlation between the two shares is fairly low ($r^2 = 0.43$), given the low resolution of both soil datasets. If the median values of the shares are calculated at the county level, the peatland area is much more diluted than at the municipality level $p_{GL,c}$ (8.9 %) and $p_{AL,c}$ (3.6 %).

The results obtained on the basis of the GUEK differ in three essential aspects from those based on the BUEK. First, peatland is much more widely distributed. At least some agriculturally used peatland can be found in nearly 39 % of all German municipalities (3,884). Second, the correlation between $p_{AL,m}$ and $p_{GL,m}$ ($r^2 = 0.20$) is markedly lower for the GUEK as compared to the respective BUEK figure. Third, a much smaller share of peatland is located in areas with high shares of peatland (Fig. 1). For instance, according to the GUEK, 90 % of the peatland is

located in municipalities with shares of UAA on peatland below 53 %, while the respective figure for the BUEK is 70 %. Furthermore, the extent of areas with high shares of peatland is greatly underestimated when data are aggregated at the county level. The GUEK indicates a wider distribution of peatland than the BUEK, hence more farms are using peatland, but each to smaller extent (Fig. 1). However, we started from two general assumptions to obtain a first impression of the number of farms that would be affected by changes of peatland management. First, that farms use land only in their municipality, and second, that for all farms, the values for p_{AL} and p_{GL} are equal to the average value for the municipality they are located in ($p_{AL,m}$ and $p_{GL,m}$). Between 5 (GUEK) and 10 % (BUEK) of German farms are located in municipalities where the share of UAA on peatland exceeds 20 %. However, these farms manage between 50 (GUEK) and 75 % (BUEK) of the German UAA on peatland.

Table 3 indicates the relevance of the agricultural production on peatland, particularly for dairy and beef. With respect to the activities related to arable land, the differences between the BUEK and GUEK mainly reflect the different extent of arable land on peatland according to these two sources. The level of spatial aggregation of both datasets (soil and land use) prior to their intersection generally only has a small influence on the results. The results obtained by an approach where data is aggregated per municipality differ by >10 % from the ones calculated based on county averages only for pigs and poultry, maize, and potatoes and sugar beets, indicating a certain insensitivity of the productive orientation to the soil conditions within one county.

Table 4 compares the agricultural utilization of peatland in the four study areas. If the BUEK is used to delineate

Fig. 1 Cumulative density distribution of the UAA on peatland and the share of affected farms as a function of the share of UAA on peatland and data source (BUEK, GUEK). *Source* Calculations based on BUEK, GUEK, DLM and FSS. *BUEK* Soil map of Germany, *GUEK* Geological map of Germany, *UAA* Utilized agricultural area

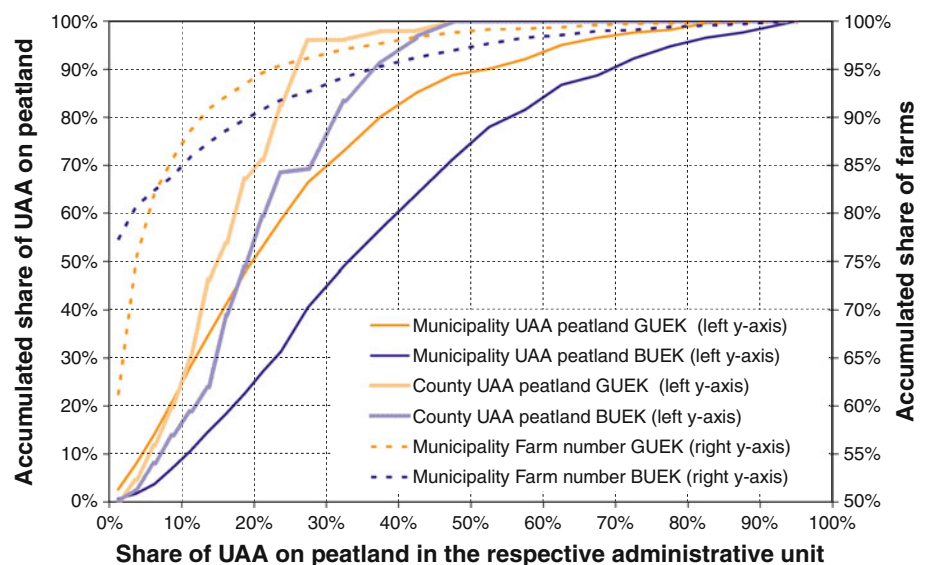


Table 3 Relevance of agricultural production on peatland for major types of livestock and crops in 2007

Delineation of peatland	Share of the German stock (measured in LU) or cropped area			
	BUEK		GUEK	
	Municipality (%)	County (%)	Municipality (%)	County (%)
Data aggregated per				
Dairy cows	9.3	9.1	8.1	8.2
Bulls	12.0	11.5	9.6	9.7
Other grazing livestock	9.6	9.3	8.6	8.4
Pigs and poultry	7.5	8.9	5.0	6.0
Maize	7.8	6.7	3.6	3.3
Other cereals	4.6	4.6	2.1	2.1
Potatoes and sugar beets	5.3	4.9	2.6	2.3

Source Calculations based on BUEK, GUEK, DLM and FSS
 BUEK soil map of Germany,
 GUEK geological map of Germany
 LU Livestock units

Table 4 Agricultural utilization of peatland in the four study areas in 2007

		AL on UAA (%)	GL on UAA (%)	MFA on UAA (%)	AFC on AL (%)	CC on AL (%)
BUEK	NW	49	51	70	40	60
	SO	48	52	63	23	77
	NE	53	47	56	18	82
	CE	58	42	54	20	80
	Germany	51	49	64	29	71
GUEK	NW	34	66	79	38	62
	SO	28	72	78	22	78
	NE	30	70	76	20	80
	CE	36	64	71	20	80
	Germany	32	68	78	30	70

Source Calculations based on BUEK, GUEK, DLM and FSS. Values calculated according to Eq. 3

NW north-west, NE north-east, SO south, CE center

BUEK soil map of Germany, GUEK geological map of Germany

UAA utilized agricultural area, AL arable land, GL grassland, MFA main forage area, AFC arable forage crops, and CC cash crops

peatland, approximately half of the UAA on peatland is used as arable land. This share is only higher in CE, where peatland areas are generally more scattered. The land use is fairly similar in SO, NE and, apart from the share of arable land, also in CE. NW differs with respect to two important aspects from the other areas. First, the share of arable forage cropping (mainly maize) on the arable land is, at the expense of cash cropping, twice as high as in the other areas. Second, in NW, the share of arable land on UAA rose by 7 % between 1999 and 2007, while it remained constant in the other areas.

Overall, for all four studied areas, the area of arable forage cropping increased from 111,000 ha in 2003 to 156,000 ha in 2007, while the area of cash cropping declined by 27,000 ha in the same period. The expansion of arable forage cropping occurred mainly in NW and NE. In these two areas, arable forage cropping increased by 42,000 ha (45 %). This change is comparable to the developments on mineral soils in these two areas. The

expansion of arable forage cropping is probably linked to the cultivation of maize for biogas because the number of grazing livestock units (GLUs) dropped in these two areas by 7 % (peatland) or 5 % (mineral soils) in the same period.

Analyses of the GUEK generally confirm the results obtained from the BUEK with the marked exemption of p_{AL} . The share of p_{AL} is in all study areas 15 to 23 % lower as the GUEK reports 300,000 ha less arable land on peatland. Consequently, the absolute differences in ha regarding the changes in crop rotation on arable land are roughly halved when compared to the figures based on the BUEK.

Connection Between Land Use and the Distribution of Peatland

For the localization indices, we present only the results for the different experiments regarding data resolution at the municipality level. The localization indices were calculated

based either on an average value regarding the share of agricultural land on peatland (cf. Eq. 4 (I_2, I_4)) or on values differentiated for grassland and arable land (cf. Eq. 3 (I_1, I_3)).

The share of grassland on the UAA is positively correlated with p_{UAA} (Fig. 2). If p_{UAA} exceeds a value of 30 (GUEK) to 50 % (BUEK), the share of grassland on the UAA is 1.5 to 3 times higher than the national average. This share is equivalent to grassland shares of 43 to 86 %. An analysis based on the GUEK indicates the site-dependency of grassland utilization more clearly than an analysis based on the BUEK because, in the results derived from the GUEK, the slopes of the localization indices are steeper, and the localization indices reach higher levels. Localization indices calculated on county data (Eqs. 5, 6) reach

similar levels compared to the municipality analyses (not shown). However, high localization indices (>1.5) are obtained at smaller shares of peatland (above $\sim 25\text{--}30\%$).

The greater share of grassland in areas with higher shares of peatland does not imply that the utilization of peatland is less intensive compared to mineral soils. Irrespective of the data aggregation chosen, the data demonstrate a clear positive relationship between the stocking density and the share of peatland (Fig. 3). The increasing stocking densities in peatland-rich areas can mainly be attributed to a concentration of dairy farming in these areas (data not shown). The grazing livestock that are maintained at low input levels (i.e., suckler cows and their offspring, sheep and horses) barely respond to a shift in the share of peatland (data not shown).

Fig. 2 Localization index for grassland as a function of the share of utilized agricultural area (UAA) on peatland for different types of spatial data aggregation (data for 2007). *Source* Calculations based on BUEK, GUEK, DLM and FSS. *BUEK* Soil map of Germany, *GUEK* Geological map of Germany. Average share: grassland area on peatland calculated based on $p_{UAA,m}$. Differentiated share: grassland area on peatland calculated based on $p_{GL,m}$

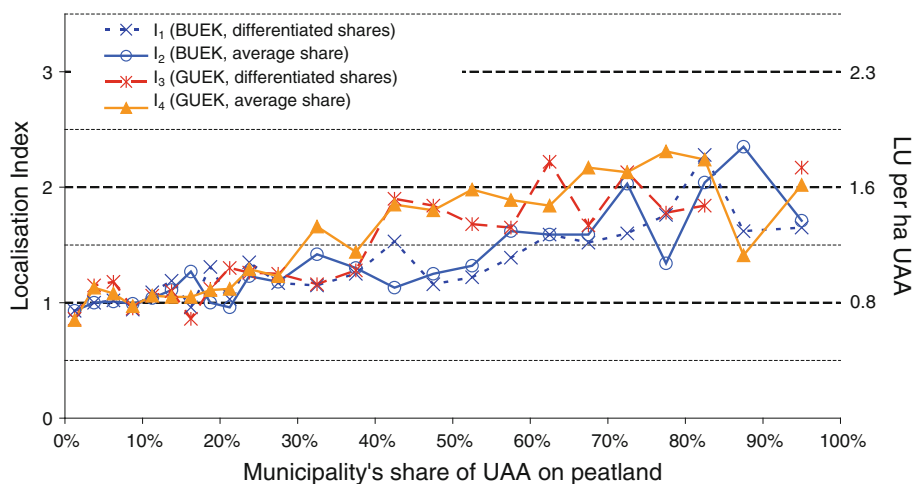
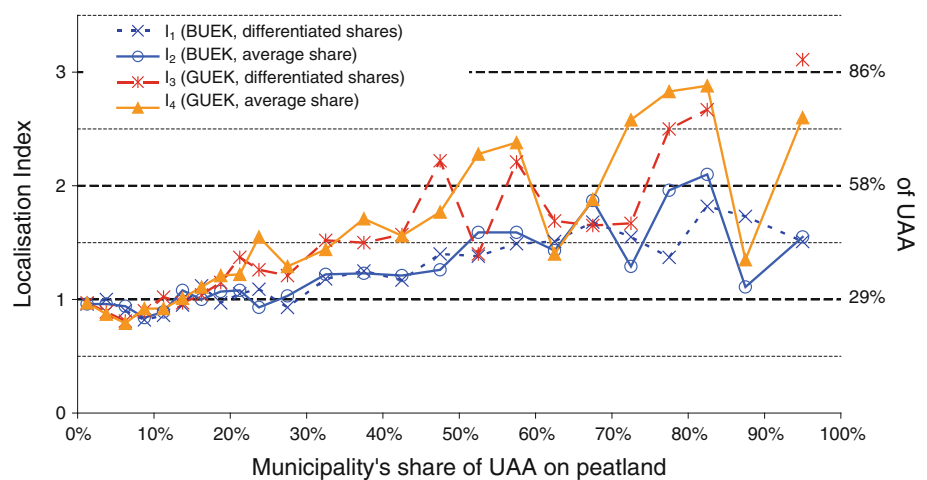
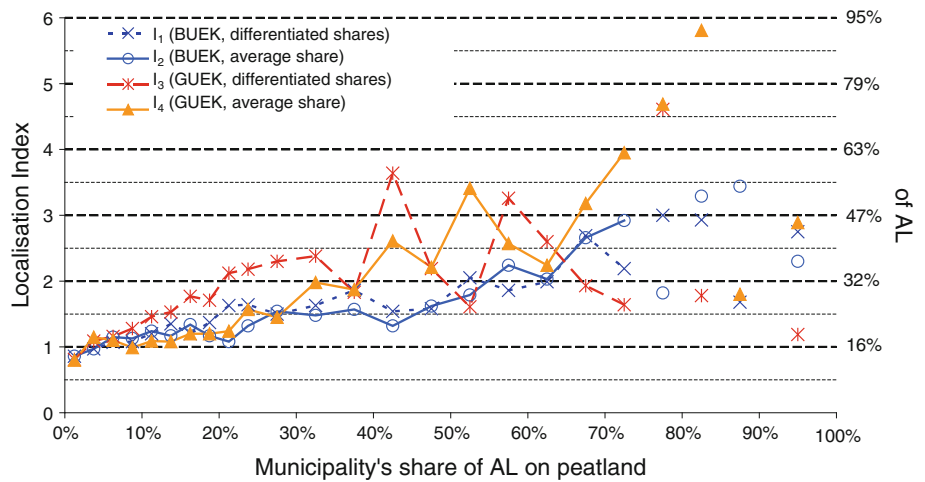


Fig. 3 Localization index for the stocking density in livestock units (LU) per ha of utilized agricultural area (UAA) as a function of the share of UAA on peatland for different types of spatial data aggregation (data for 2007). LU per ha UAA. *Source* Calculation based on BUEK, GUEK, DLM and FSS. *BUEK* soil map of Germany, *GUEK* geological map of Germany. Average share: LU on peatland

calculated based on $p_{UAA,m}$. Differentiated share: LU on peatland calculated based on $p_{GL,m}$ (sheep, horses, and suckler cows and associated offspring (heifers and calves)), $p_{AL,m}$ (pigs and poultry), and $p_{UAA,m}$ (bulls and dairy cattle and associated offspring (heifers and calves))

Fig. 4 Localisation index for maize as a function of the share of arable land (AL) on peatland for different types of spatial data aggregation (data for 2007). *Source* Calculations based on BUEK, GUEK, DLM and FSS. BUEK soil map of Germany, GUEK geological map of Germany. Aggregates <200 observations are not connected with a line. Average share: maize area on peatland calculated based on $p_{UAA,m}$. Differentiated share: maize area on peatland calculated based on $p_{AL,m}$



Regarding the utilization of arable land, the increasing importance of dairy farming is mirrored by the positive correlation between $p_{AL,m}$ and the share of maize, which is by far the most significant arable forage crop in Germany. Even if the data are interpreted cautiously, maize is two to three times as frequent than the national average in areas with high shares of peatland, implying that maize reaches average shares of 30 to 50 % in the crop rotation in municipalities where $p_{AL,m}$ exceeds values of 20 to 40 % (Fig. 4).

Intensity Gradient in the Use of Peatland

In the following section, we describe the intensity gradient in the use of peatland with the help of cumulative density distributions (CDDs). We only present the results derived from the GUEK because the differences in the distribution that are derived from the two soil datasets are generally small. The data for the study area CE are not shown because this study region summarizes *Laender* with a

completely divergent farm structure in West and East Germany. Generally, the method of delimiting the area of UAA on peatland has a negligible impact on the results, and the data aggregated at municipalities lie between the bounds defined by the aggregation at the farm level on one side and the county level on the other. In most cases, the intensity gradients between the municipalities are hardly separable from the respective intensity gradients between the counties. Therefore, we do not present the results obtained at the municipality level. The data at the farm level are based on $p_{AL,m}$ and $p_{GL,m}$ while for the county-level data, $p_{UAA,c}$ is used. Regarding the interpretation of the plots, the steeper the depicted curve, the smaller the observed gradient.

The agricultural utilization of peatland is closely linked to livestock husbandry in NW and SO (Fig. 5). This is indicated by the median stocking density which is more than twice as high as in NW and SO compared to NE. However, a high median intensity does not imply that all the peatland is intensively managed. In particular, in NW

Fig. 5 Cumulative density distribution of the utilized agricultural area (UAA) on peatland as a function of the stocking density in livestock unit (LU) per ha UAA in the four study areas in 2007 at farm and county levels. *Source* Calculations based on GUEK, DLM and FSS. NW north-west, NE north-east, SO south, CE center

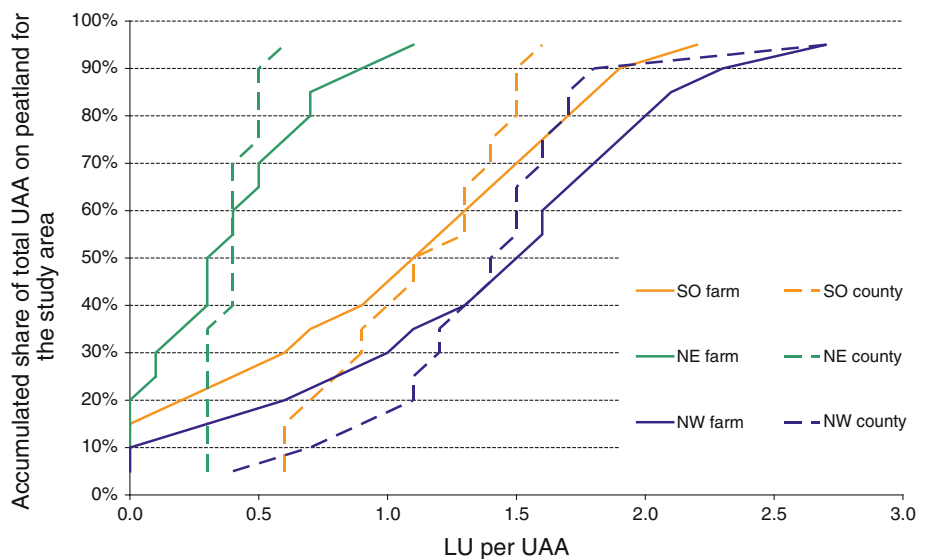
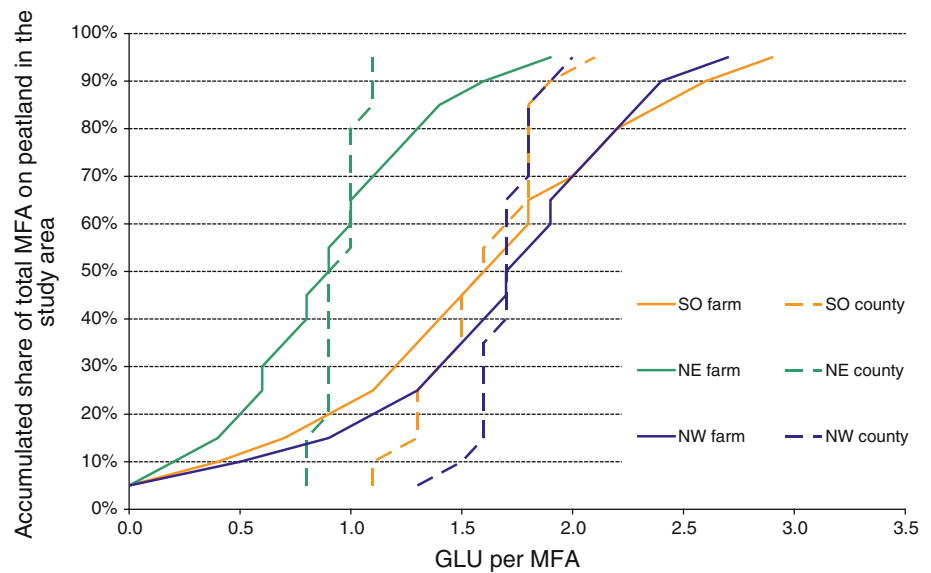


Fig. 6 Cumulative density distribution of the main forage area (MFA) on peatland as a function of the stocking density of grazing livestock (GLU; GLU per ha MFA) in the four study areas in 2007 at the farm and county levels. *Source* Calculations based on GUEK, DLM and FSS. *NW* north–west, *NE* north–east, *SO* south, *CE* center



and SO the densities vary widely, not only between farms but also on a regional level (counties).

The results are rather similar if the stocking density of grazing livestock (i.e., cattle, sheep and horses) is related to the main forage area (Fig. 6). In all study areas, farms without any grazing livestock manage 5 to 10 % of the main forage area (MFA) on peatland. Only in NE is a relevant share (~ 15 %) of the MFA on peatland stocked with less than 0.5 LU per ha. A total of 0.5 LU per ha MFA is roughly the limit regarding the number of animals that can be fed from an unfertilized and undrained pasture on peatland (Dierschke and Briemle 2002, p. 153). Between 40 % (SO) and 60 % (NW) of the MFA on peatland is stocked with more than 1.7 LU per ha. These densities can only be sustained if grassland is intensively fertilized and well drained or if a significant share of the arable land is devoted to arable forage cropping.

Between the study areas, the intensity of the forage cropping and its distribution differs both with respect to the stocking density and with regard to the composition of the stock. In NE, farms without any dairy cattle manage 60 % of the main forage area on peatland. This share is more than twice the share of NW and SO. As dairy cattle demand much more energy and protein rich fodder compared to other grazing livestock, the high share of dairy cattle in NW and SO implies a more intensive grassland management, irrespective of the stocking density.

Discussion

The following discussion is divided into three parts. First, we summarize our main findings with respect to the agricultural utilization of German peatland. Second, we discuss

the relevance of MAUP in this context. Third, we highlight the consequences with respect to the assessments of GHG abatement potentials and costs.

In all of the studied regions, between 70 and 80 % of the peatland is devoted to the production of forage for grazing livestock. Despite the predominance of forage cropping, we observed marked differences in the land use intensity among the studied areas, particularly with respect to stocking density. The intensity is fairly low in northeastern Germany, and a significant share of the land is used by suckler cows. In southern and northwestern Germany, the utilization intensity is much higher, and dairy farming is prevalent. In northwestern Germany, pig and poultry fattening farms put additional pressure on the utilization of peatland. These farms need the peatland areas for both the provision of fodder and for the spreading of manure to comply with restrictions limiting manure application (Schaller and Kantelhardt 2009).

With respect to the distribution of grassland, we clearly identified a localization effect, and this effect is derived from three observations. First, in most municipalities, $p_{GL,m} > p_{AL,m}$ irrespective of the soil map. Second, with increasing resolution of the soil map, the difference between $p_{GL,m}$ and $p_{AL,m}$ increases for a given municipality. Third, the share of grassland on UAA is positively correlated with $p_{UAA,m}$.

The area of arable land on peatland delimited with the help of the BUEK is more than twice the respective figure for the analysis based on the GUEK. Assuming that the GUEK, due to its higher resolution provides a more realistic picture of the “true” extent and distribution of peatland, this difference can be explained as follows: mineral soils in the vicinity of peatland or in areas where peatland is widespread are far more likely to be used as arable land

compared to the local average. Due to the coarse scale of the BUEK, these areas are often falsely classified as peatland.

Placing the impact of the changing data resolution on the obtained results in the context of the other studies is difficult because assessments of the data quality and impact of the survey scale for non-remote sensing data are generally lacking (Bach and others 2006; Sbresny 1997). Based on the experience from quality assessments of remote sensing data, one would assume that the increase in the scale from the BUEK to the GUEK will lead to an expansion of the peatland area. This could not be confirmed. However, our results are in line with the results from two study areas in Lower Saxony, each roughly 100 km² in size (Lösel 2005).

The reported relative differences of 25 % between the two sources regarding the extent of peatland is not unusual if compared with results obtained from the quality assessments for remote sensing data. Regarding the extent of a particular land-use type, the differences between two datasets frequently exceed 30 %, even if only very general land use types are differentiated and a large area is covered (e.g., Keil and others 2004; Giri and others 2005).

Despite the difference regarding the extent of the arable land on peatland, both soil datasets produce similar results with respect to the crop rotation and the intensity gradient if agricultural activity data of the same resolution are used. Generally, the analyses based on the GUEK display a more pronounced response of the agricultural utilization to the share of peatland on UAA.

We assume that the presented approach still overestimates the extent of agricultural land on peatland and, in particular, the area of arable land on peatland for the following reasons. First, the original field data sources used for the delineation of peatland in the GUEK may be up to 100 years old (Zitzmann 2003). Agricultural utilization of peatland is frequently accompanied by a decline of the peat layer by more than 1 cm per year (Olezcuk and others 2008). Therefore, it is likely that peatland with a relatively shallow histic layer already “degenerated” to mineral soils (Eggelsmann and Barthels 1975). As mineralization rates for arable land are generally higher, this “degeneration” may particularly affect peatland with a long history of arable use.

The two data sources available for a German-wide assessment of peatland areas differ significantly in their reporting. While the BUEK reports 1.28 million ha of agriculturally used peatland, the respective figure for the GUEK is 0.98 million ha. This difference is caused by the much smaller extent of arable land on peatland reported in the GUEK. Using the emission factors reported in the German national GHG inventory (UBA 2010) and the land use derived from the GUEK instead of using the BUEK, the GHG emissions from the agricultural use of peatland

decline by 36 %, while the peatland area is only 29 % smaller compared to UBA (2010). However, the currently used default emission factors do not take into account the positive correlation between land use intensity and GHG emissions, particularly for peatland used as grassland (Höper 2007; Drösler and others 2011). This correlation is due to the fact that intensive and productive grassland demands well-drained soils. However, in Germany, one cannot assume that extensively managed grassland on peatland is necessarily characterized by a high water table. The low productivity may be the result of other factors (e.g., low levels of variable inputs (especially fertilizers), due to an agrarian structure unfavorable for an intensive grassland management).

The distribution of agriculturally used peatland depends on the used spatial resolution regarding both soil and land use data. The differences in the distribution of peatland have major implications if one assesses the economic consequences of changes in peatland management. Farms are generally fairly immobile. This fact particularly holds true for grazing livestock farms because, on these farms, most capital is fixed in buildings, and it is not economical to transport the roughage (i.e., grass, silage or hay) over large distances. Consequently, the more affected the production of a farm is by a mitigation measure on peatland, the fewer and more costly are the options for adaptation (Kantelhardt and Hoffmann 2001). Hence the utilization of county averages would imply an underestimation of the true costs (lower average share of UAA on peatland), while the use of the BUEK would lead to an overestimation (more areas with a high share of UAA on peatland).

In all of the studied areas, pronounced differences exist between the farms within one municipality regarding land use intensity. Given constant GHG emissions on a per ha basis it is advisable to first abandon and rewet the agriculturally used peatland with the lowest production. Such a strategy would minimize the negative offsets per ha induced by indirect land use changes. Additionally, from an economic point of view, a strategy of exploiting these differences in intensity and compensating each farmer only on the magnitude of his personal opportunity costs is cost-saving. However, abandoning and rewetting peatland requires larger contingent areas, implying that every singly affected land user (owner) must accept the rewetting. As to whether the intensity differences at the local level can be exploited for the efficient design of a nationwide mitigation strategy or whether the payments must be set at a level that is acceptable for the vast majority of farmers is an open issue. In contrast to northeastern Germany, the land use intensities of neighboring farms differ widely in southern and northwestern Germany. The more homogenous intensities in the North-East increase the likelihood for the implementation of a differentiated compensation scheme.

Outlook

The current approach for determining land use on peatland and, in consequence, the assessment of the GHG emissions from organic soils, can be improved in several ways. First, an updated high-resolution data (e.g., at scale of 1:25,000) mapping of the different organic soils and in particular, their drainage status, would allow an improved assessment of the affected area, the use of differentiated GHG emission factors, and a more differentiated calculation of the abatement costs. Second, the agricultural census data indicate a pronounced heterogeneity with respect to land use intensity between the farms within one municipality. However, with the farm structure survey's data resolution, depicting the specialization of farms in response to soil properties on a level below the resolution of the municipality is impossible. Farms that utilize peatland are likely to run at a different intensity than the municipality's average, e.g., the grassland on peatland might be extensively grazed by suckler cows or heifers, while the grassland on mineral soils might be intensively managed to feed the dairy herd. Despite the problems regarding data confidentiality, the utilization of the geo-referenced IACS (Integrated Accounting and Control System) that was established to administer the European support payments for agriculture is the most promising option to overcome this bottleneck. Third, field studies are required to clarify the question of whether the intensity of grassland management and the level of the water table are correlated in practice. If this is the case, the emission factors that are differentiated according to the intensity could be used. Otherwise, the information on intensity could only be used for cost estimates. Fourth, GHG emission factors must be established for organic soils other than peatland. This classification is particularly relevant because the GUEK reports another $0.45 \cdot 10^6$ ha of agriculturally used organic soils other than peatland ("Anmoor" (e.g., histic gleysols)) or peatland covered by an inorganic top layer, of which, $0.19 \cdot 10^6$ ha are used as arable land.

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Glossary

Arable forage crops: Summarizes all arable crops grown to feed grazing livestock (e.g., green maize, alfalfa, temporary grassland, clover) normally produced on farm and not sold via a market; concentrates (feed grains) are not part of the arable forage crops.

Arable land: Area cultivated with annual crops and temporary grassland fields in ley farming systems. Temporary grassland in ley farming systems is only included in the arable area if the area is ploughed at least once in a five-year interval.

Cash crop: All crops grown to be sold primarily at commodity markets (crops for human consumption or industrial use).

Grazing Livestock: Cattle, sheep, goats and horses.

Main forage area: Summarizes all crops (including grassland) grown to feed grazing livestock.

Suckler cow: A cow which rears its own calf and is later used for beef production; normally grazing during the vegetation period and supplemented only with low levels of concentrates.